DEVELOPMENT OF PORTABLE 1O STAGES MARX GENERATOR

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This thesis is dedicated to my lights in this world, who have given me the opportunity of an education from the best institutions and support throughout my life,

" my loved parents".

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ABSTRACT

High voltage equipments are often placed in open air and they are often exposed to lightning strike as well as surge voltage. They are sustaining high surge voltage during the lightning phenomena. To achieve better protection of all such power equipments and quality power supply, these voltages should be simulated and test the above said equipments in laboratories, Marx generator is the commonly used. This generator produces lightning impulse voltages of 1.2/50 μs duration. This project describes the development of a cost effective and easily portable compact 10 stages Marx Generator capable of producing lightning impulses voltage up to 25kV. In addition, three different experimental circuits of HV DC supplies have been made. The highest output was 2.5 kV DC which was taken as the main supply for the experimental and simulated Marx generator circuit. This generator can be used by small scale industries and academic institutions to demonstrate impulse voltages and also to perform testing on insulators of lower rating in laboratory. A total of 10 stages of both simulated, experimental Marx impulse generator circuit was designed and the impulse waves were recorded. The simulated recorded impulse waveform was compared with the standard impulse wave with front time of 1.2 μ seconds and tail time of 50 μ seconds. Both of circuits, the efficiency of each stages was calculated and the percentage of error in the front and tail time was also found out as well as the effects of the circuit parameters on the impulse waveform characteristics were also studied. The simulation was done with the help of Pspice Software Simulation. In this work, the comparison in terms of magnitude of the experimental and simulated 10 stages Marx generator circuit has been carried out as well as its illustrative curve has been drawn. These results have confirmed the validity of the proposed method and they were in close agreement.

ABSTRAK

Peralatan voltan tinggi sering diletakkan di udara terbuka dan peralatan tersebut sering terdedah kepada serangan kilat dan voltan lonjakan. Peralatan voltan tinggi mengekalkan voltan lonjakan tinggi dalam fenomena kilat. Untuk mencapai perlindungan yang lebih baik bagi semua peralatan kuasa dan kualiti bekalan kuasa, voltan, simulasi dan menguji perlu dibuat di atas peralatan yang dinyatakan di dalam makmal, penjana Marx ini adalah biasa digunakan. Penjana ini menghasilkan tempoh voltan impuls kilat pada 1.2 / 50 µs. Projek ini menggambarkan pembangunan kos padat 10 peringkat berkesan dan mudah alih penjana Marx mampu menghasilkan impuls kilat sehingga 25kV. Di samping itu, tiga litar uji kaji yang berbeza bekalan HV DC telah dibuat. Keluaran tertinggi ialah 2.5 kV DC yang diambil sebagai bekalan utama bagi eksperimen dan simulasi litar penjana Marx. Penjana ini boleh digunakan oleh industri kecil dan institusi akademik untuk menunjukkan voltan impuls dan juga untuk melakukan ujian ke atas penebat penarafan yang lebih rendah di dalam makmal. Sebanyak sepuluh peringkat bagi kedua-duanya simulasi ini, eksperimen impuls litar penajan Marx telah direka dan gelombang telah direkodkan. Gelombang impuls merekodkan simulasi dan dibandingkan dengan gelombang impuls standard dengan masa depan 1.2 µ saat dan masa ekor 50 µ saat. Bagi kedua-dua litar, kecekapan setiap peringkat telah dikira dan peratusan kesilapan di depan dan ekor masa itu juga mendapati serta kesan parameter litar kepada ciri-ciri gelombang juga dikaji. Simulasi ini dijalankan dengan bantuan Pspice Perisian Simulasi. Dalam kajian ini, perbandingan dari segi eksperimen magnitud dan simulasi sepuluh peringkat litar penjana Marx telah dijalankan serta lengkung ilustrasi telah disediakan. Keputusan ini telah mengesahkan tempohnya pada kaedah yang dicadangkan dan telah menjadi perjanjian dekat.

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LIST OF SYMBOLS AND ABBREVLATIONS

AC	-	Alternative current
DC	-	Direct current
HV	-	High voltage
C_1	-	Charging capacitor
C_2	-	Discharging capacitor
R_1	-	Front resistor
R_2	-	Tail resistor
T_1	-	Front time
T_2	-	Tail time
G	-	Sphere gap
V_{PEAK}	-	Peak voltage
$V_{(t)}$	-	Input voltage
$V_{(O)}$	-	Output voltage
E	-	Energy
IEC	-	International Electrotechnical Commission
UTHM	-	Universiti Tun Hussein Onn Malaysia

CHAPTER 1

INTRODUCTION

1.1 Introduction

Most of the high voltage equipments such as power transformers, surge arresters, circuit breakers, isolators and high tension transmission line towers are placed in transmission substations. As these equipments are very costly and important for maintaining continuity of power supply, there safety should be the major priority for an electrical engineer. These equipment must tolerate not only the rated voltage which corresponds to the highest voltage of a particular system, but also over voltages. Accordingly, it is mandatory to test high voltage (HV) apparatus during its development stage. Protection of power system is an important aspect for the continued service of the electrical power system [1-4]. Mostly the protection of electrical power depends on the performance of insulation systems under transient over voltage conditions arises due to lightning and switching applications. Transient over voltages along with the abrupt changes in the state of power systems, e.g. switching operations or faults are known as switching impulse voltages and that due to lightning are known as lightning impulse voltages. It has become generally identified that switching impulse voltages are usually the prevalent factor affecting the design of insulation in HV power systems for rated voltages of about 300 kV and above [5-6]. Hence attention is required for these two types of over voltages. So in order to protect these equipments a prototype of the same can be used to test against lightning strikes.

A Marx Impulse generator is used to generate lightning impulse voltage. The magnitude and nature of test voltage varies with the rated voltage of particular equipment. It was originally described by E. Marx in 1924 and is primarily used because of its ability to repetitively provide high bursts of voltages especially when the available voltage sources cannot provide the desired voltage levels [1]. This generator consists of multiple capacitors that are first charged in parallel through charging resistors by a high-voltage, direct-current source and then connected in series and discharged through a test object by a concurrent spark-over between the sphere gaps. The generated voltage from impulse generator must satisfy the standard values of voltage defined by the International Electro techno Commission in order to qualify as a standard impulse voltage that can be used for testing purposes [7]. The standard methods of measurement of high-voltage and the basic methods for application to all types of apparatus for alternating voltages, direct voltages, switching impulse voltages and lightning impulse voltages are laid down in the important national and international standards. Although the wave shapes of impulse voltages occurring in the system may vary extensively.

International Electro technical commission IEC60060 specifies that the insulation of transmission line and other equipments should withstand standard lightning impulse voltage of wave shape 1.2/50 μs and for higher voltages (220 kV and above) it should withstand standard switching impulse voltage of wave shape 250/2500μs. The tolerances [3-4] that can be allowed for the impulse wave are given by ±30% for time to front and ±20% for time to tail. [5-7].

In this work, an attempt has been made to develop a compact, inexpensive, portable 10 stages Marx impulse generator circuit for demonstration of lightning impulses in academic institutions. This 10 stages Marx generator circuit, was simulated by using PSpice software and the same circuit was made practically. In addition, three different sorts of HV DC supply were made to test the practical circuit as well as to provide HV DC supply in laboratory. Finally, the simulated and experimental results were compared in terms of their magnitudes.

1.2 Project Objectives

Over voltages on power lines create a great danger for the equipment, continuity of supply and more specifically the safety of personnel. Hence research in this area specifically the study of Impulse waves, its generation, its nature and characteristics is desired. As the power lines and equipments are exposed to the atmosphere, hence lightning strike is a common phenomenon. The main complication in high voltage engineering is the construction of proper high voltage insulation with minimum dimension at low cost. The only way to protect the power systems is to test the equipment's insulation strength by subjecting them to high impulse voltages and accordingly design the insulation of these equipments. Therefore, prediction of impulse withstands voltage for power equipments are very much essential which can only be achieved if we closely monitor the generation and characteristics of impulse waves. This motivates the need for practical high voltage impulse generation using Marx Impulse generator. Marx generators are used to provide very high voltage pulses for the examining the strength of insulation of electrical equipments such as large power transformers, or insulators used for aiding power transmission lines. The main objective of the thesis is:

i. To know characteristics of lightning voltage strikes.
ii. To develop 10 stages Marx Generator circuit using PSpice software to generate a waveform impulse voltage.
iii. To develop a practical 10 stages circuit model of Marx generator and to produce an impulse voltage.
iv. To provide three different kinds of high voltage DC supply in UTHM laboratory.
v. The final goal is to compare the theoretical values of peak lightning voltage obtained in simulation with those recorded in practical circuit.

1.3 Scope Of Project

The reason in writing the scope of this project is to make sure the project could be work regularly and not out of target. Thus, the research is more focus on :

i. Construct circuit of impulse generator using OrCAD PSpice version 9.1 software simulations.
ii. Collect the information about Marx impulse generator and how to design it properly.
iii. The lightning voltage's characteristics which can be a reference to design lightning protection and detection.
iv. 10 stages of Marx generator circuit will be constructed and designed using a prototype model on a reduced scale (1.2/50 μs), and 2.5 kV DC as input .
v. Collect the information about high voltage DC and construct three different circuits to be provided in the laboratory.
vi. Network analyzer is used to measure experimental result and measurements will be compared with simulated result.

1.4 Problem Statement

Each of the projects has their own problem to be discussing before starting the project. By stating the problem statement it easy to know the purpose of doing this project and what are the problem to be solved. Below are the problem statements for this project.

i. Lack of portable impulse generator mainly for research and education purpose.
ii. There are applications where they are needed for low magnitudes of impulse voltage(less than 5 kV).
iii. To provide an alternative for studying the generator impulse voltage in such a way that modification can be made easily.

iv. To provide portable HV supplies in the laboratory for education purpose.

v. To provide hands-on experience to the students in developing HV related stuff, for example; HV resistive divider.

1.5 Organization of Thesis.

This project report consists of five chapters, chapter one is introduction, chapter two is impulse generation for HV review, chapter three is implementation of simulation and experiment of HV impulse Generator, chapter four is development of portable 10 stages Marx generator and chapter five is conclusion and future recommendation.

Chapter one will be explain about the high voltage definition, history and standard. This chapter also states the problem for the project, objective and scope of the project report.

Chapter two will discuss about the theory of impulse voltage, there are five parts in this chapter to be discuss. First part about the theory of impulse voltage, second part types of impulse testing, third part impulse voltage circuit, fourth and five are about equipment and component that are use in this project.

Chapter three is the methodologies for the whole processes of project. In project methodology will explain the whole project procedure from starting finding and research the topic until choose the best circuit. For simulation method will explain the step of simulation project circuit. Lastly experiment methods are explaining the step in the experiment project.

In chapter four is discussing about the project result, this chapter consist of simulation and experimental result. In simulation part will discuss the result of output waveform and experiment part will discuss the output lightning voltage from the Multimeter and oscilloscope by using resistive voltage divider.

Finally, the last chapter five is the conclusion of the whole project report and suggestions.

CHAPTER 2

IMPULSE GENERATION FOR HV: REVIEW

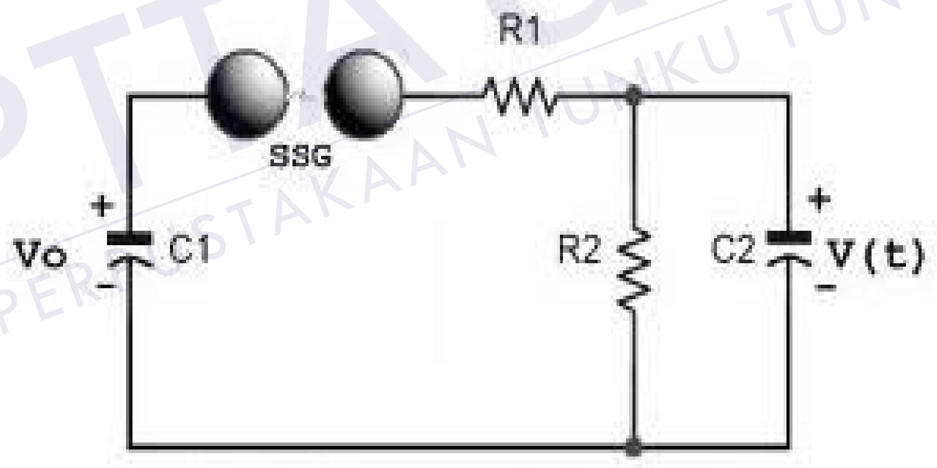
2.1 Background

High voltage technology was introduced at the beginning of the last century for electrical power generation and transmission systems. Long before that efforts have been made to study the lightening characteristics inside laboratory to carry out the tests on power system equipment in order to protect them from hazardous of lightning strike. A number of theories on lightening formation and generation have been presented [5]. Since the exploration on lightening started, efforts have been made to realise the lightening phenomenon inside laboratory so that the characteristics of the lightening can be studied more accurately and tests on power system equipment can be carried out. Many authors have presented their work about the generation of lightening impulse inside laboratory [3-15]. Marx has been the important guiding principle in generating lightening impulse voltage [8-13]. Almost in every paper Marx theory has been used but some paper have modelled the same principle differently for different application. Modified Marx generator has also been studied extensively [13-14]. In almost all the papers discussed so far has employed capacitive loading for getting the impulse responses. Marx circuit has been widely used in the generation of high repetition voltage pulses, high power microwaves where rise time ranges in the ns region. For accurate measurement of high voltage pulses through measuring instruments, measurement techniques and procedures have also been proposed [4], [9].

2.2 Single Stage Marx impulse Circuit

2.2.1 Standard

The energy storage capacitor C_1 is charged from the high voltage direct current (HVDC) power supply. The output waveform is controlled by the interaction of the front resistor R_1 and the tail resistor R_2 with the energy storage capacitor C_1 and the load C_2. The sphere gap in the circuit is a voltage limiting or voltage sensitive switch. Capacitor C_1 charges from a dc source until the sphere gap breaks down. The time of breaking down of sphere gap is very short.



Figurer 2.1: Single Stage Impulse Generator Circuit (Standard Marx circuit)

Charging voltage in large impulse generator can be of the order of mega volt (MV). The wave shaping network in the impulse generator consists of R_1, R_2 and C_1. Resistor R_1 basically damps the circuit and regulates the front time while R_2 is the discharging resistor through which C_1 will discharge. C_2 is the load which represents the capacitance of the load itself and capacitance of other elements parallel with the load. Capacitor C_1 discharges into the circuit comprising of R_1, R_2 and C_2, when break down of the sphere gap takes place [5].

Usually the impulse generator incorporates a load capacitance which is adequately large that the output waveform shape does not change considerably with changes in sample capacitance. The resistors R_1, R_2 and the capacitance C_2 form the wave shaping network. R_1 will primarily damp the circuit and control the front time T_1. R_2 will discharge the capacitors and therefore essentially control the wave tail. The capacitance C_2 represents the full load, i.e. the object under test as well as all other capacitive elements which are in parallel to the test object [1], [2].

Fast impulse or slower impulses can be generated if switching modifications are applied in the impulse generating circuits. One probable way of generating longer pulse is to add an inductance in series with R_1 [5], [7]. The difference in circuit arrangement will have different efficiency for the impulse generator. The dc voltage can be generated by the use of rectifier circuits. The rectifier used in the simulation is full wave rectifier circuit. The smoothness of dc value is not much of concern as it has to only charge the capacitor to peak. A sphere gap is a switch and the voltage across the sphere gap builds up as a voltage building up across capacitor takes place. Normally the sphere gaps are allowed to fire naturally or for smooth operation it can be fired through control methods.

2.2.1.1 Circuits For Producing Impulse Wave

Impulse waves can be produced in a laboratory with a combination of a series R-L-C circuit with over damped conditions or by the combination of two R-C circuits. Various equivalent circuit models that produce impulse waves are shown in Figure 2.2(a) to 2.2(d). Out of these circuits, the ones shown in Figure 2.2(b) and (c) are commonly used for experimental purpose. Circuit is shown in Figure 2.2(a) has some limitations as the front time and tail time over a wide range cannot be varied. Commercial generators implement circuits is shown in Figure 2.2(b) to 2.2(d) [l-4].

and the load C_2. The only difference is that the switch here acts as a potential divider that divides the tail resistor. The advantage of this method is that this circuit design helps in proper shaping of the impulse wave as the standard wave i.e. It helps in reducing the errors in rise time and tail time. The rise in peak voltage is not that considerable [6].

2.3 Multi Stage Marx Impulse Circuit

2.3.1 Standard

Due to the difficulties faced in very high voltage switching of the spark gap, increase in circuit element size, requirement of high direct current voltage to charge capacitor and difficulties in corona discharge suppression from the structures during charging period the extension of the single stage to multistage impulse generator is made[5-7].

A multistage generator is developed by cascading smaller single stage generator to generate high magnitude of output voltage. The primary requirement is to charge capacitors through the rectifier circuit and when all the capacitor reaches to the fully charged state then spark gaps are allowed to break down causing the capacitors to add in series. As a result the nominal output voltage is equal to the input voltage multiplied by the number of stages in the impulse generator circuit. At first, n capacitors are charged in parallel to a voltage (V) by a high voltage DC power supply through the resistors. The spark gaps used as switches have the voltage V across them, but the gaps have a breakdown voltage greater than V, so they all behave as open circuits while the capacitors charge. The last gap isolates the output of the generator from the load; without that gap, the load would prevent the capacitors from charging [1-3]. To create the output pulse, the first spark gap is caused to break down (triggered); the breakdown effectively shorts the gap, placing the first two capacitors in series, applying a voltage of about 2V across the second spark gap. Consequently, the second gap breaks down to add the third capacitor to the stack, and the process continues to sequentially break down all of the gaps. The last gap connects the output of the series stack of capacitors to the load. Ideally, the output voltage will be nV, the number of capacitors times the charging voltage, but in practice the value is less.

2.3.2 Improvement.

The Improved Impulse Marx generator works same as the standard Impulse Marx generator i.e. the energy storage capacitor, C_1, is charged from the high voltage direct current (HVDC) power supply. The output waveform is controlled by the interaction of the front resistor R_1 and the tail resistor R_2 with the energy storage capacitor C_1 and the load C_2. The only difference is that the switch here acts as a potential divider that divides the tail resistor. The advantage of this method is that this circuit design helps in proper shaping of the impulse wave as the standard wave i.e. it helps in reducing the errors in rise time and tail time. The rise in peak voltage is not that considerable [6].

In multistage Marx generator circuit resistive voltage divider are used in order to minimize the level of voltage to a measureable value across each capacitor [5],[6]. It consists of two impedances which are connected in series and a tapping is introduced in between these resistors in order to connect the sphere gap. Usually charging resistance is chosen to limit the charging current to about 50 to 100mA, while the generator capacitance is chosen such that the product of charging resistance and generator capacitance is about to 10s to 1 minute [4]. The discharge time constant will be too small (microseconds), compared to the charging time constant which will be few seconds. For designing the circuit of Marx Impulse Generator various equations were used. The standard impulse wave was calculated using:

$$v = v_0 * \left[e^{-\alpha t} - e^{-\beta t}\right] \tag{2.1}$$

Where, α and β are constants of microsecond values. V0 is the applied DC voltage. The efficiency of each stage was given by

$$\text{Efficiency} = \frac{V}{V_0} \tag{2.2}$$

Where, V is the peak output voltage; V_0 is the applied DC voltage. It can also be given by

$$\text{Efficiency} = \left(\frac{1}{1+(C2*n)C1}\right) + \left(\frac{1}{1+\left(\frac{R1}{R2}\right)}\right) \tag{2.3}$$

CHAPTER 5

GENERAL CONCLUSION AND FUTURE RECOMMENDATION

5.1 Conclusion

A multistage generator circuit could be designed by using different types of circuits' construction and formulas that every type gives different values of components that should be used. Although, the designed circuits are not the same, output waveform of the surge should be fulfill the standard impulse waveform.

In this project, a Marx generator circuit was built practically and implemented in the simulation with the OrCAD PSpice software environment. It is found that the overall simulated results of waveforms were close to the standard impulse generator (IEC60060 surge standard, 1.2/50 μs) for all the stages Marx generator circuit. The ratio of C_1/C_2 was taken as 40 in each stage. However, the front and tail time of the practical circuit could not be computed because the suitable front and tail resisters are not provided.

The impulse waveform was governed by the values of front resistor and tail resistor. The front time gets affected accordingly with the change in the front resistor value as well as peak voltage changes. For simulation, all sphere gaps were replaced with a simple switch in Pspice Software.

The waveform of impulse generator could be in positive or negative shape (refer to peak voltage). It depends on the initial charge of capacitors either positive or negative. For negative charge, the waveform should be in negative peak voltage and vise versa for positive charge.

The experimental circuit was tested by using three different made HV DC supplies and the highest one was taken as main supply for simulated and practical circuit. The experimental output lightning voltage was captured by using different position of output gaps.

In this work, 10 stages Marx generator circuit was modeled, simulated and designed practically. The experimental circuit was divided in two parts, HV DC supply is the first form and impulse Marx circuit is the second form. The effects of the circuit parameters on the impulse wave characteristics have been also studied and it is found that as long as the proper parameter selection is made, the circuit will produce the standard waveform from the Standard voltage generator.

5.2 Future Recommendation

Several recommendations of the future work were listed as following:

i. For impulse testing, a stray capacitance to ground could be added to a resistive voltage divider . A high voltage is applied to the top of the divider and a stray capacitance is distributed along the length of the resistor stack. The purpose of adding a stray capacitor is to make a front time nearly matches to the standard value. In addition, stray capacitance would also be added to each stage tail resistor. The tail resistors are shorter in length than the voltage divider and would have a smaller value of stray capacitance.

ii. Double transistor Fly-back transformer driver circuit could be used to generate a higher voltage of DC (about 4-8 kV). In this project, a single transistor Fly-back transformer was used at the maximum source (battery) of 12 V. However, in double transistor circuit, 24 DC voltage cold be used.

iii. Load of Marx generator circuit. In this project, capacitor of value 0.025 nF has been used to be as load. In other project, a load could be replaced by using different kinds, such as resistive or inductive load (R-L load).

REFERENCES

[1] Suthar, J. L., Laghari, J. R., Saluzzo, T. J., “Usefulness of Spice in High Voltage Engineering Education”, Transactions on power system, Vol.6 (August 1991): pp. 1272- 1278.

[2] Zhou, J. Y. and Boggs, S. A., “Low Energy Single Stage High Voltage Impulse Generator”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol.11 (August 2004): pp.507-603.

[3] Vecchio, M. D. R., “Determining Ideal Impulse Generator Settings from a Generator - Transformer Circuit Model”, IEEE Transactions on Power Delivery, Vol.17, (January 2002): pp.142-148.

[4] Mondal, Jolly. Modelling and Simulation of Impulse Voltage Generator using Marx Circuit. Diss. National Institute of Technology, Rourkela, 2014.

[5] Kuffel, John, E. Kuffel, and Walter S. Zaengl. High voltage engineering fundamentals. Newnes, 2000.

[6] Wadhwa, C.L., “High Voltage Engineering” New Delhi, New Age International Publishers, 2007.

[7] Kamarudin, Muhammad Saufi, et al. "Impulse generator and lightning characteristics simulation using Orcad PSpice software." (2008).

[8] R.A. Fitch, “Marx and Marx like High Voltage generators”, IEEE Trans. Nuclear Science, Vol. 19 (1971): pp. 190-198.

[9] A. G. Halim, “High Voltage measurement technique”, Master of Applied Science thesis, Dept. of Electrical Eng., University of Brititsh Columbia, Vancuver, Canada (June 2007).

[10] Neuber, A.A., Chen, Y.J., Dickens, J.C., Kristiansen, M.: A compact, repetitive, 500kV, 500J, Marx generator. In: IEEE Pulsed Power conference, Monterey, A, 2005, pp 1203-1206.

[11] Prabaharan, T., Shyam, A., Shukla, R., Banerjee, P., Sharma, S., Deb, P., Verma, R., Kumar, R., Das, R., Das, B., Adhikary, B.: Development of 2.4ns rise time, 300kV, 500MW compact co-axial Marx generator. In: Indian journal of Pure & Applied Physics, Volume 49, January 2011, pp 64-72.

[12] Anders, A., Brown, I. G., MacGill, R. A., Dickinson, M., R., “Vacuum-Spark Metal Ion Source Based on a Modified Marx Generator”, IEEE Transactions on Plasma Science, Vol. 25 (August 1997): pp.718-721.

[13] Baek, J. W, Yoo, D. W., Rim, G. H., Lai, J. S., “Solid State Marx Generator Using Series-Connected IGBTs”, IEEE Transactions on Plasma Science, Vol. 33 (August 2005): pp.1198-1204

[14] T.Prabaharan, A.Shyam, R. Shukla, P.Banarjee, S. Sharma, P Deb, R Verma, R. Kumar, R. Das, B Das and B Adhikary, “Development of 2.4 ns Rise Time, 300 KV-500 M Compact co-axial Marx generator”, Indian Journal of Pure and Applied Physics, Vol.49(01) (January 2011): pp. 64-72.

[15] S.C. Tean, (2008, February 21). The Effects of Fast Rise Multiple Lightning Impulse on the Electrical Breakdown Characteristics of MOV. Available: http://eprints.utm.my/2143/1/SinChokTeanMED2006TTT. pdf.

[16] Zivanovic, Rastko, et al. "Identification of the resonant-grounded system parameters by evaluating fault measurement records." Power Delivery, IEEE Transactions on 19.3 (2004): 1085-1090.

[17] Chen, Shih-Ming, et al. "A cascaded high step-up dc–dc converter with single switch for microsource applications." Power Electronics, IEEE Transactions on26.4 (2011): 1146-1153.

[18] Gallagher, T. J., and Pearmain, A. J., High Voltage Measurement, Testing and Design (John Wiley & Sons Ltd., 1983), p. 122.

[19] Schwab, Adolf J., High-Voltage Measurement Techniques (The M.I.T. Press, Cambridge, Massachusetts, and London, 1972), p. 11.

[**20**] Kuebrich, K., et al. "Influence of nonlinear magnetic inductance in passive mains harmonic reduction circuits." Applied Power Electronics Conference and Exposition, 2005. APEC 2005. Twentieth Annual IEEE. Vol. 2. IEEE, 2005.

[**21**] Singh, Deepak Kumar. Novel Application of LabVIEW in High Voltage Engineering. Diss. National Institute of Technology, Rourkela, 2012.

[**22**] Dwivedi, C. K., and M. B. Daigvane. "Multi-purpose low cost DC high voltage generator (60kV output), using Cockcroft-Walton voltage multiplier circuit."Emerging Trends in Engineering and Technology (ICETET), 2010 3rd International Conference on. IEEE, 2010.

[**23**] Dai, J.; Wang, Z.D.; "A Comparison of the Impregnation of Cellulose Insulation by Ester and Mineral oil," Dielectrics and Electrical Insulation, IEEE Transactions on , vol.15, no.2, pp.374-381, April 2008.